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Chowdhury et al.

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(54) **APPARATUS EMPLOYING MULTIFERROIC MATERIALS FOR TUNABLE PERMITTIVITY OR PERMEABILITY**

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G02B 6/00 (2006.01)
H01P 3/12 (2006.01)

(52) **U.S. Cl.** **385/122**; 333/239

(58) **Field of Classification Search** ..... 385/122, 385/123, 147; 333/239; 360/123.01, 135; 343/787, 911 R, 700 MS
See application file for complete search history.

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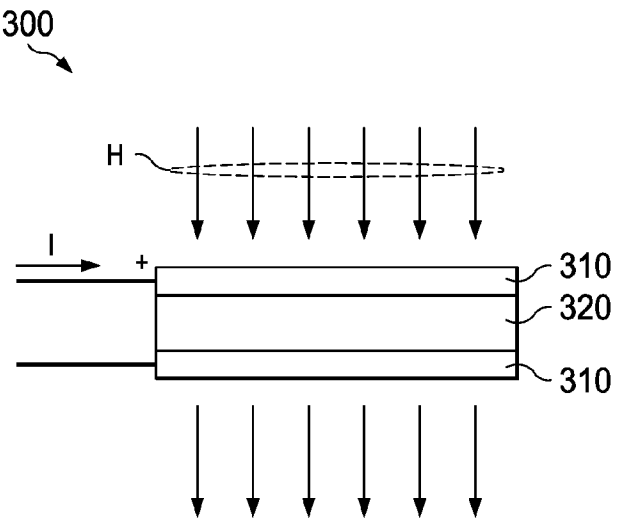
(74) *Attorney, Agent, or Firm* — Hitt Gaines, PC

(57) **ABSTRACT**

An apparatus has a waveguide that includes a multiferroic medium. A controller is configured to apply a mechanical strain or a control electric or magnetic field to the multiferroic medium. The multiferroic medium has a dielectric permittivity or magnetic permeability that is responsive to the strain or the control field.

20 Claims, 10 Drawing Sheets



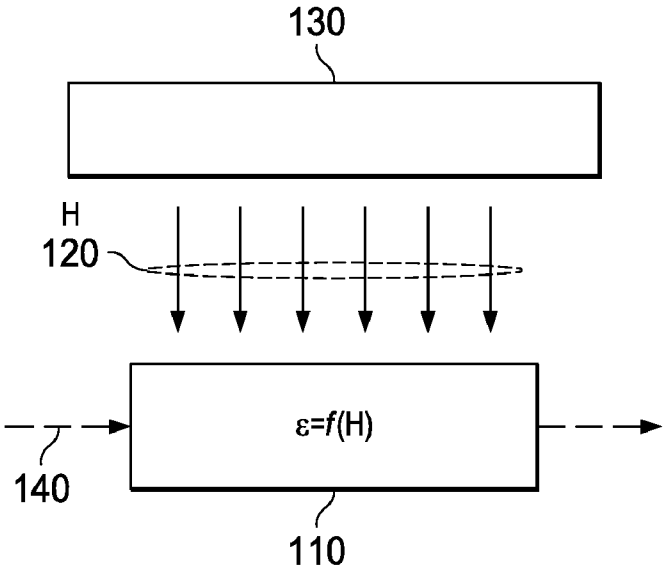


FIG. 1A

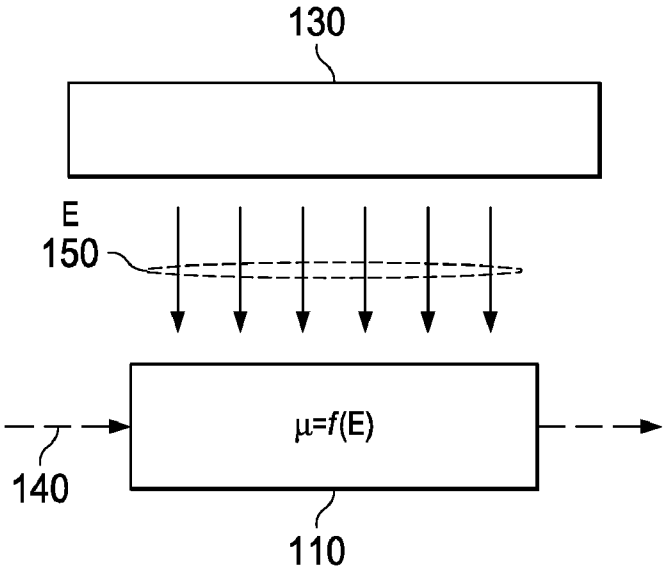


FIG. 1B

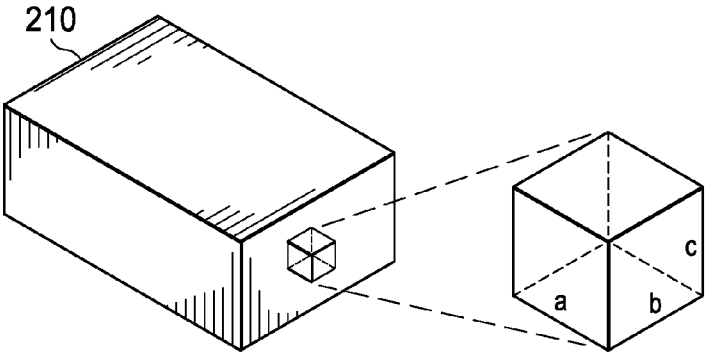


FIG. 2A

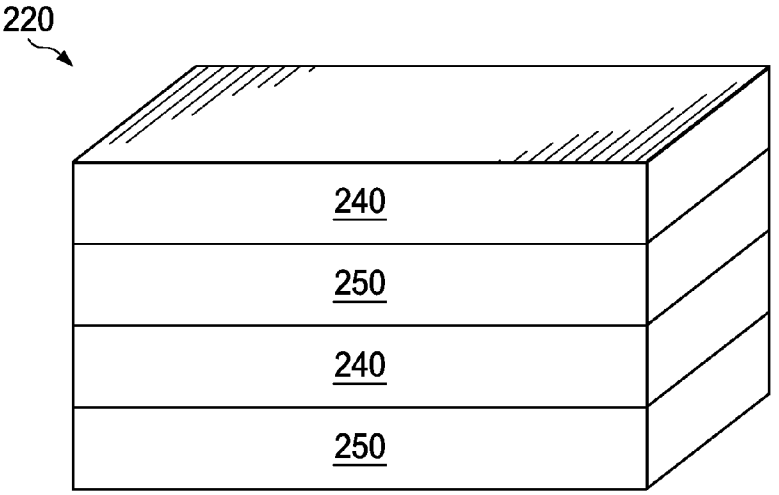


FIG. 2B

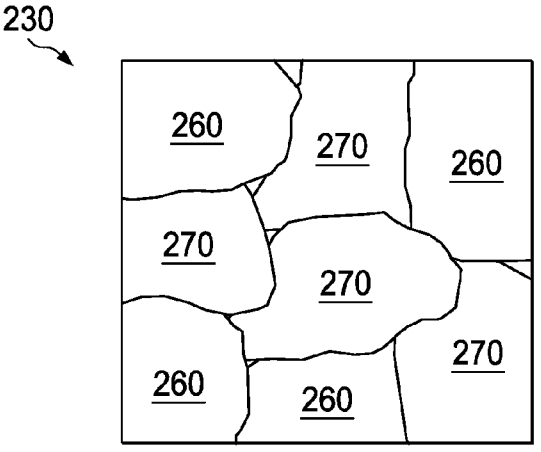


FIG. 2C

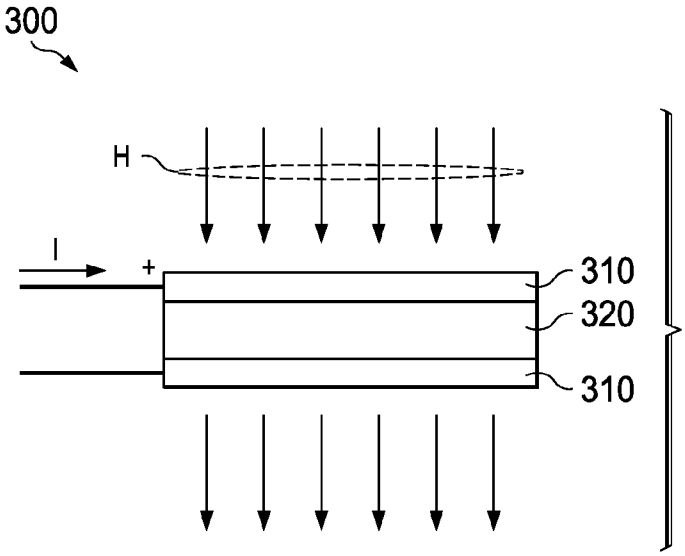


FIG. 3A

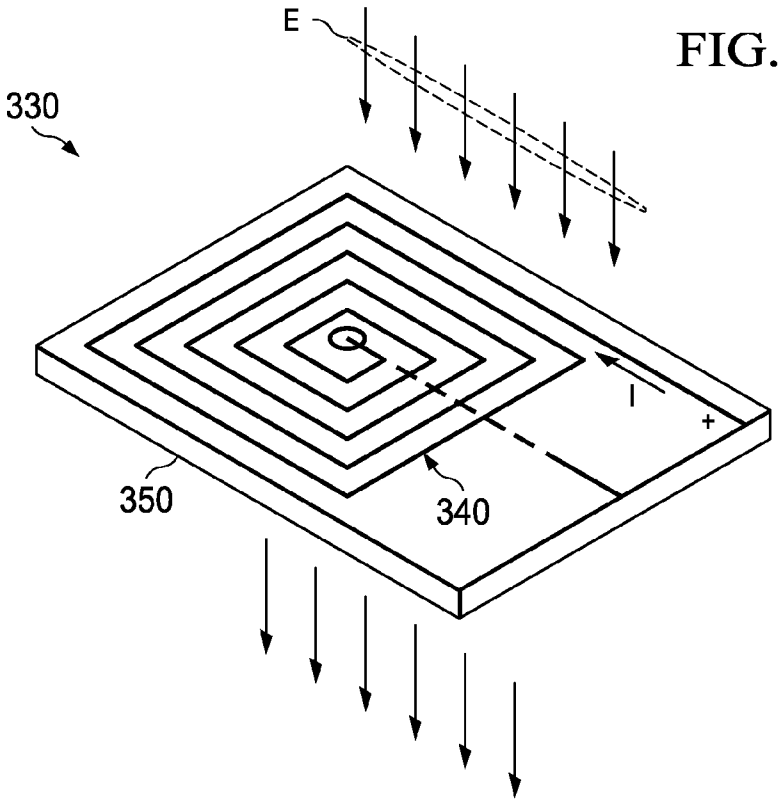


FIG. 3B

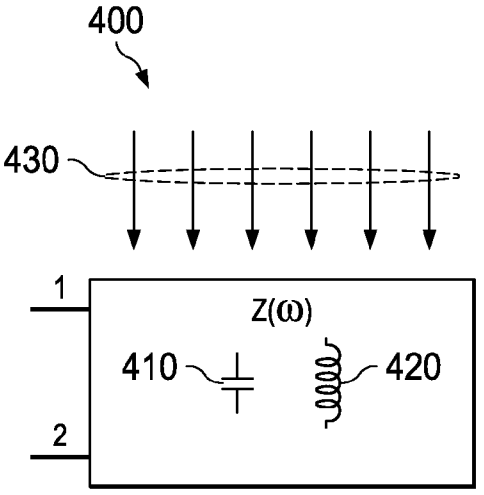

400
430
1
Z(ω)
410
420
2

FIG. 4

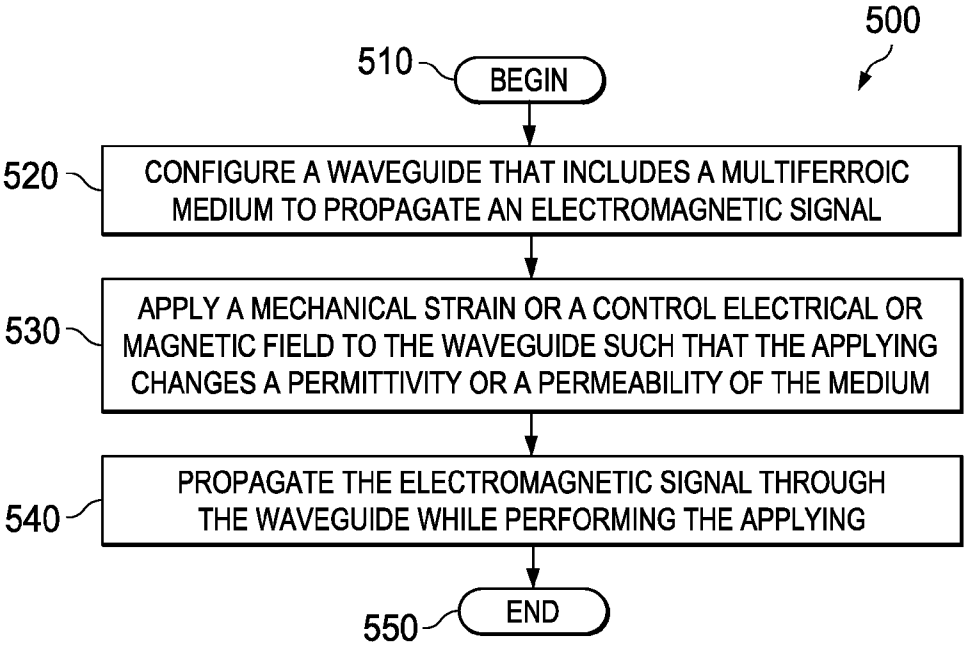

500
510
BEGIN
520
CONFIGURE A WAVEGUIDE THAT INCLUDES A MULTIFERROIC MEDIUM TO PROPAGATE AN ELECTROMAGNETIC SIGNAL
530
APPLY A MECHANICAL STRAIN OR A CONTROL ELECTRICAL OR MAGNETIC FIELD TO THE WAVEGUIDE SUCH THAT THE APPLYING CHANGES A PERMITTIVITY OR A PERMEABILITY OF THE MEDIUM
540
PROPAGATE THE ELECTROMAGNETIC SIGNAL THROUGH THE WAVEGUIDE WHILE PERFORMING THE APPLYING
550
END

FIG. 5

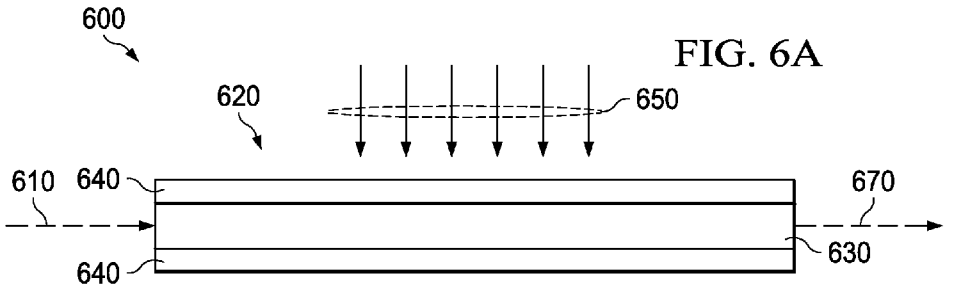


FIG. 6A

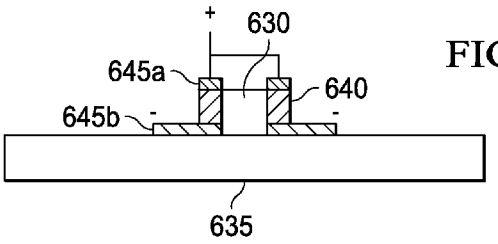


FIG. 6B

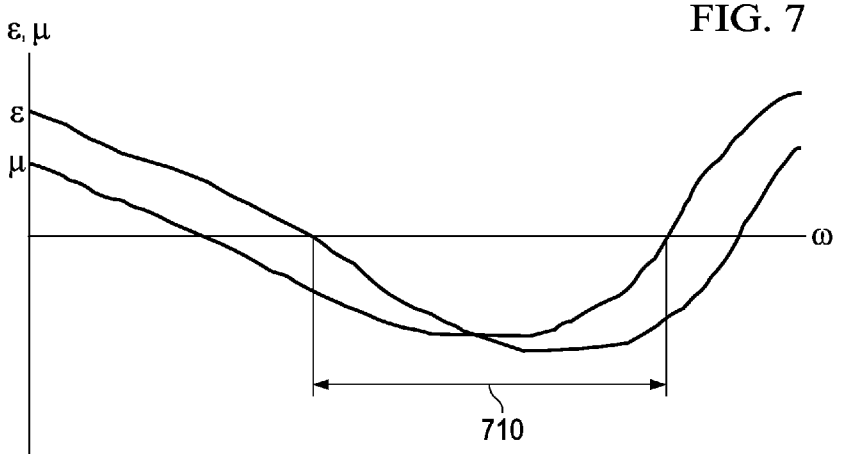


FIG. 7

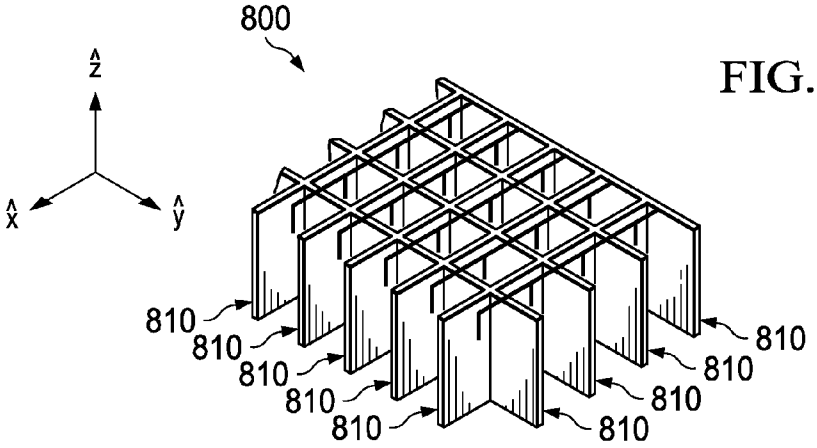

800
ẑ
x̂
ŷ
810
810
810
810
810
810
810
810
810
810

FIG. 8A

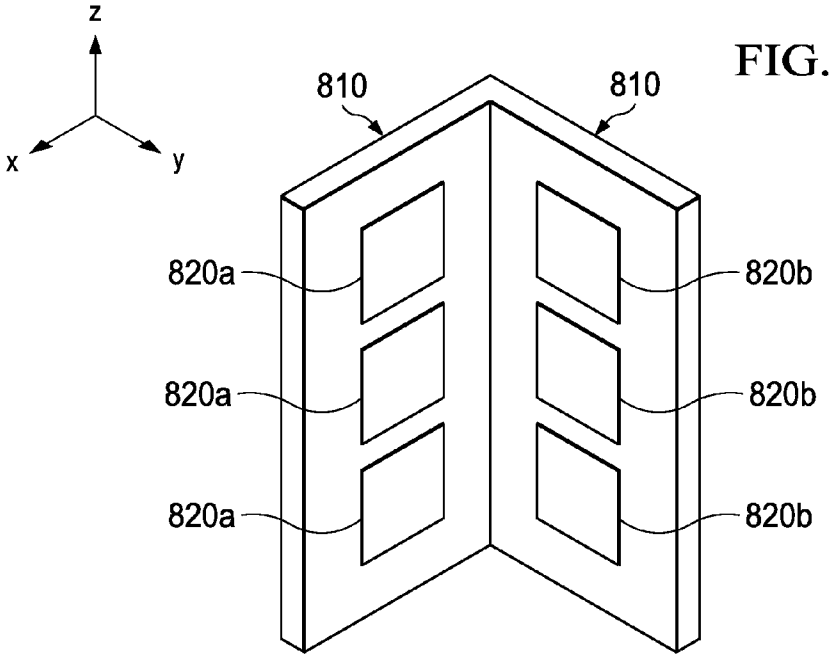

z
x
y
810
810
820a
820a
820a
820b
820b
820b

FIG. 8B

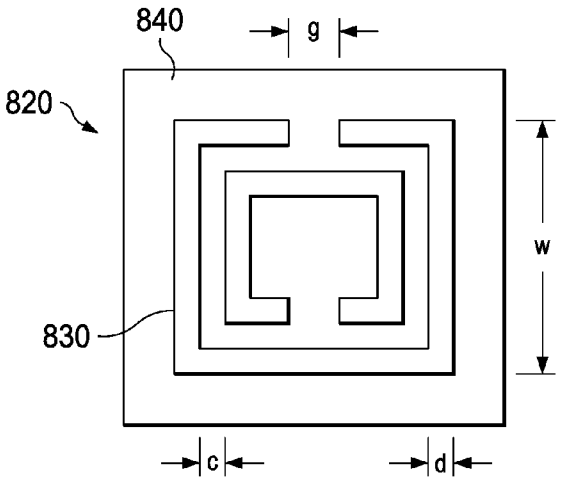

840
g
820
w
830
c
d

FIG. 8C

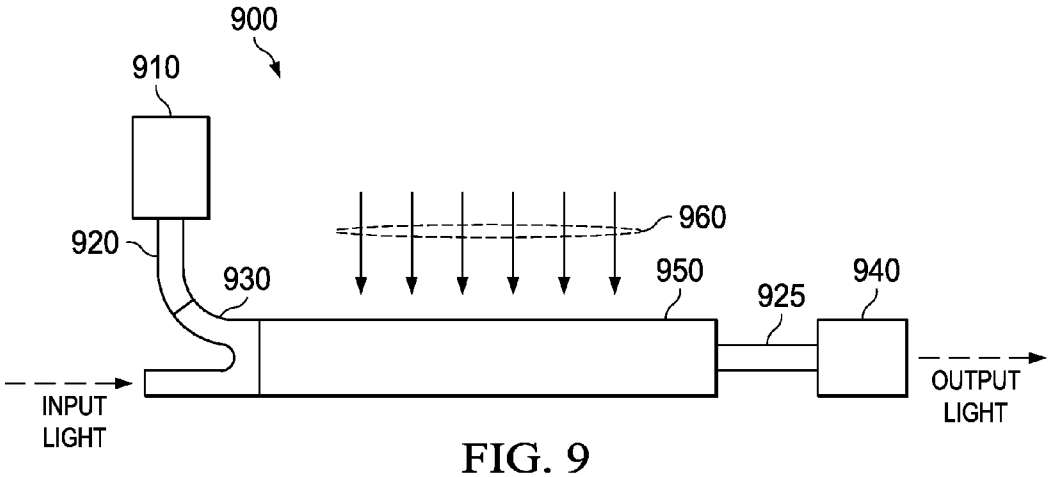

900
910
920
930
960
950
925
940
INPUT
LIGHT
OUTPUT
LIGHT

FIG. 9

FIG. 10

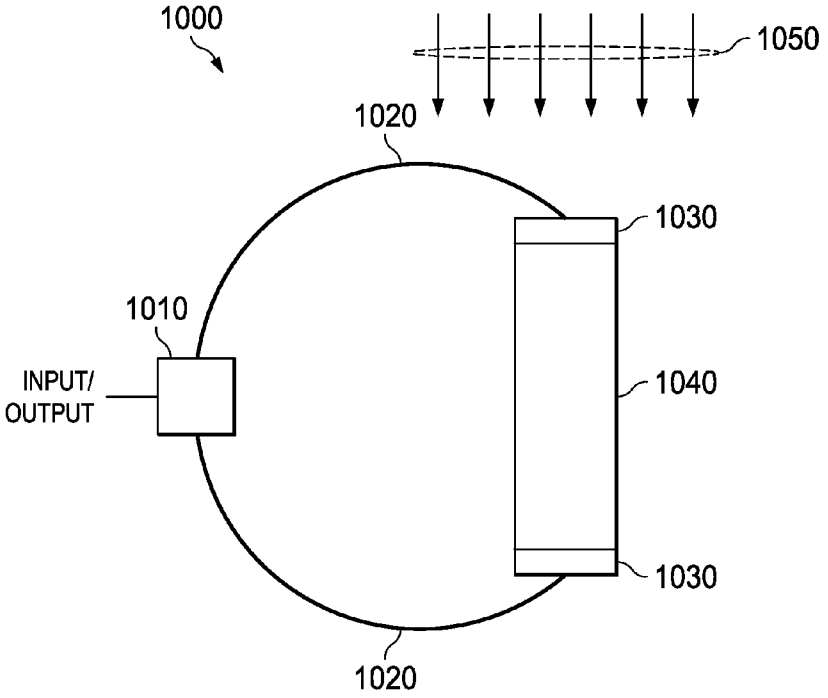
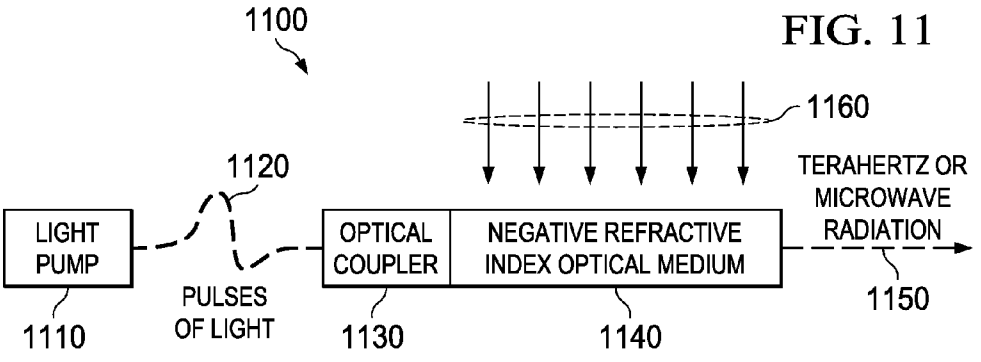

1000
1050
1020
1030
1010
INPUT/
OUTPUT
1040
1030
1020

FIG. 11


1100
1160
1120
TERAHERTZ OR
MICROWAVE
RADIATION
LIGHT
PUMP
OPTICAL
COUPLER
NEGATIVE REFRACTIVE
INDEX OPTICAL MEDIUM
PULSES
OF LIGHT
1110
1130
1140
1150

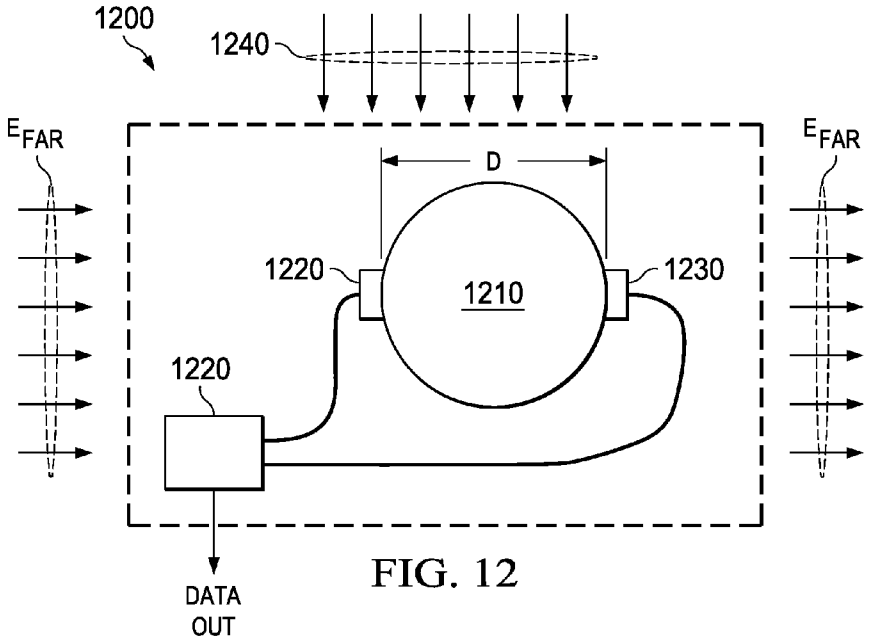

1200
1240
E_{FAR}
E_{FAR}
D
1220
1210
1230
1220
DATA
OUT

FIG. 12

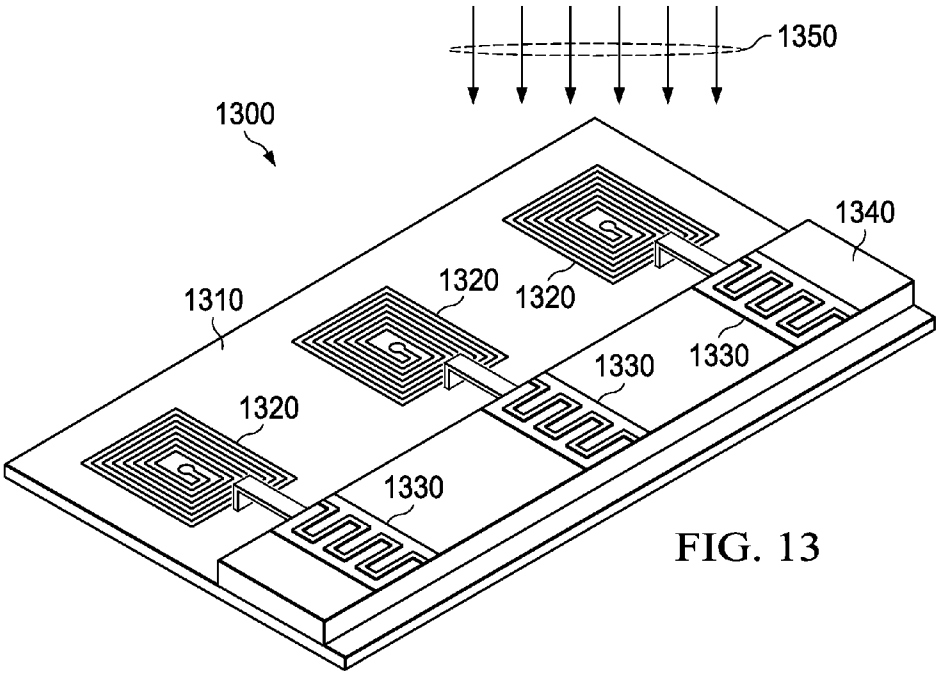

1350
1300
1340
1310
1320
1320
1330
1330
1320
1330

FIG. 13

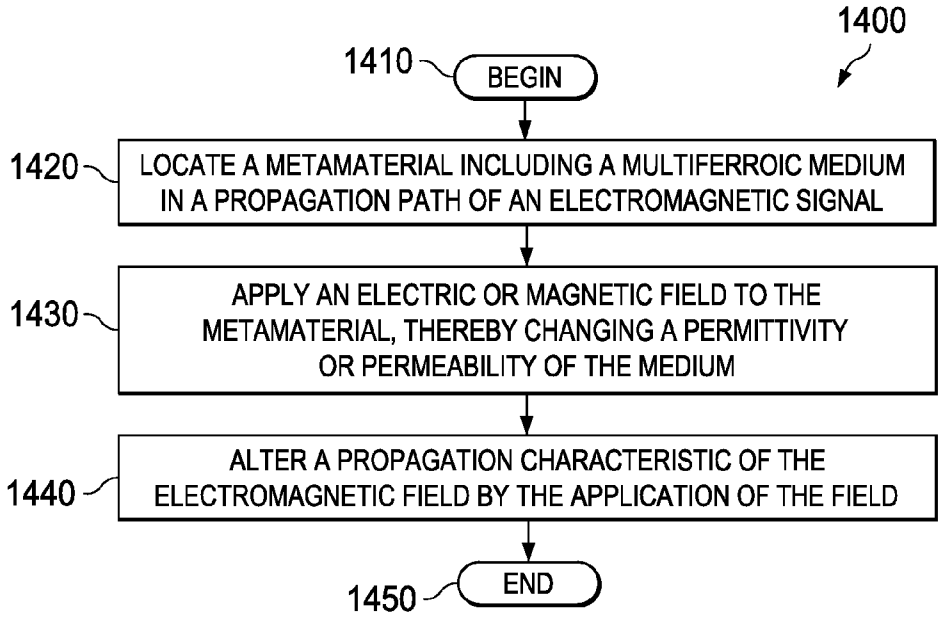

1400
1410
BEGIN
1420
LOCATE A METAMATERIAL INCLUDING A MULTIFERROIC MEDIUM IN A PROPAGATION PATH OF AN ELECTROMAGNETIC SIGNAL
1430
APPLY AN ELECTRIC OR MAGNETIC FIELD TO THE METAMATERIAL, THEREBY CHANGING A PERMITTIVITY OR PERMEABILITY OF THE MEDIUM
1440
ALTER A PROPAGATION CHARACTERISTIC OF THE ELECTROMAGNETIC FIELD BY THE APPLICATION OF THE FIELD
1450
END

FIG. 14

APPARATUS EMPLOYING MULTIFERROIC MATERIALS FOR TUNABLE PERMITTIVITY OR PERMEABILITY

TECHNICAL FIELD OF THE INVENTION

The present invention relates to the technical field of electronic materials and devices.

BACKGROUND

This section introduces aspects that may be helpful to facilitating a better understanding of the inventions. Accordingly, the statements of this section are to be read in this light and are not to be understood as admissions about what is prior art or what is not the prior art.

Multiferroic materials are the subject of intense research interest. Such materials may be characterized as having a coupled ferroic order parameters. Such coupling may be between, e.g., a ferromagnetic and ferroelectric response. Thus, an applied electric field may influence ferromagnetic polarization of the material, and an applied magnetic field may affect the dielectric polarization. In some cases, mechanical strain may also serve to induce an electrical or magnetic polarization.

SUMMARY

One embodiment is an apparatus that has a waveguide that includes a multiferroic medium. A controller is configured to apply a mechanical strain or a control electric or magnetic field to the multiferroic medium. The multiferroic medium has a dielectric permittivity or magnetic permeability that is responsive to the strain or the control field.

Another embodiment is an apparatus that has a plurality of unit cells. Each unit cell includes a multiferroic substrate and a reactive component supported by the substrate. The plurality of unit cells is configured to act as a metamaterial over a frequency range.

Another embodiment is a method of processing an electromagnetic signal. The method includes configuring a waveguide that includes a multiferroic medium to propagate the electromagnetic signal. A mechanical strain or a control electrical or magnetic field is applied to the waveguide such that the applying changes a permittivity or a permeability of the medium. An electromagnetic signal is propagated through the waveguide while performing the applying.

Another embodiment is a method of processing an electromagnetic signal. A metamaterial that includes a multiferroic medium is located in a propagation path of the electromagnetic signal. An electric or magnetic field is applied to the metamaterial, thereby changing a permittivity or permeability of the medium. A propagation characteristic of the electromagnetic field is changed by the applying.

BRIEF DESCRIPTION OF THE DRAWINGS

Various embodiments are understood from the following detailed description, when read with the accompanying figures. Various features may not be drawn to scale and may be arbitrarily increased or reduced in size for clarity of discussion. Reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

FIGS. **1**A and **1**B illustrate general embodiments of modulation of an input signal by a multiferroic medium;

FIGS. **2**A-**2**C illustrate homogeneous and heterogeneous multiferroic media;

FIGS. **3**A and **3**B respectively illustrate a capacitive element and an inductive element of the disclosure;

FIG. **4** illustrates a reactive network of the disclosure;

FIGS. **5** and **14** illustrate methods of the disclosure;

FIGS. **6**A and **6**B illustrate a plan and sectional view, respectively, of an optical waveguide with a multiferroic medium;

FIG. **7** illustrates a frequency-dependent $\in$ and μ;

FIGS. **8**A-**8**C illustrate a metamaterial formed using a multiferroic material;

FIG. **9** illustrates an optical wavelength converter of the disclosure;

FIG. **10** illustrates a polarization diverse apparatus of the disclosure;

FIG. **11** illustrates an negative-refractive-index device of the disclosure;

FIG. **12** illustrates an electromagnetic resonator of the disclosure; and

FIG. **13** illustrates a phased array antenna system of the disclosure.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

Embodiments described herein reflect the recognition that a multiferroic medium may be manipulated to provide tunable and efficient electronic devices such as, e.g., optical devices, antennae and filters. Such tuning may be effected, e.g., by modulating the dielectric permittivity, $\in$, and/or magnetic permeability, μ, of the medium by way of an external stimulus such as, e.g., an electric or a magnetic field. In some embodiments, a mechanical stimulus such as an applied stress or an applied strain modulates $\in$ and/or μ. (Hereinafter, for brevity, the dielectric permittivity is referred to as $\in$ or "permittivity" and the magnetic permeability is referred to as μ or "permeability" without loss of generality. Furthermore, while it is recognized that $\in$ and μ are in general complex quantities, both are used herein as substantially real quantities without notational elaboration.) In some embodiments, the index of refraction of the medium is varied by such modulation, while in other cases the impedance of a reactive network may be responsive to the stimulus. Such modulation of the dielectric and ferromagnetic properties of the medium provides a means to dynamically adjust optical or impedance characteristics of a device employing the multiferroic.

As used herein a multiferroic medium is a homogeneous or heterogeneous material exhibiting coupled ferroic properties. Coupled ferroic properties that are characteristic of a multiferroic material are, e.g., coupled ferroelectric and ferromagnetic properties. Thus, an applied magnetic field may alter the dielectric polarization of the medium, and an applied electric field may alter the magnetic polarization of the medium.

Permittivity is related to the dielectric polarization, and permeability is related to the magnetic polarization. Thus, a magnetic field may be used to change the dielectric permittivity of the medium, and an electric field may be used to change the magnetic permeability of the medium. In some cases, mechanical stress and/or strain may change the permittivity or the permeability. Restated in more general terms, an external stimulus may change the permittivity or the permeability of the multiferroic medium. The stimulus may also change the refractive index (RI), taken as $(\in\mu)^{1/2}$.

FIG. **1**A schematically illustrates a general embodiment of modulating a signal using a multiferroic medium **110**. A controller subjects the multiferroic medium **110** to an exter-

nal stimulus **120**. In this embodiment, the external stimulus **120** is a magnetic field H. Due to the multiferroic nature of the multiferroic medium **110**, the dielectric permittivity ∈ of the medium multiferroic **110** changes in response to a change in the magnetic field H. This dependence is signified by the notation ∈=f(H). An electromagnetic (EM) input signal **140** is coupled to the multiferroic medium **110**. The EM signal may be modulated by the change of ∈ caused by the stimulus **120**. The EM signal may have a frequency, e.g., in a range from near-DC (Hz) to UV (PHz).

FIG. **1**B illustrates an embodiment in which the external stimulus **150** is an electric field E. Due to the multiferroic nature of the multiferroic medium **110**, a magnetic permeability μ of the changes in response to a change in the electric field E. This dependence is signified by the notation μ=f(E). The EM signal may be modulated by the change of μ caused by the stimulus **120**.

In various embodiments, E and H are simultaneously applied to the multiferroic medium **110** to produce a desired effect on the input signal **140**. In some embodiments, the controller **130** is a source of mechanical stress and/or strain. For example, a flexible substrate upon which the multiferroic medium **110** is located may be deformed by the controller **130**.

An electric field stimulus may be applied to a structure including a multiferroic medium by a conventional method, e.g., via conductive electrodes or plates. Such electrodes or plates may be configured to provide an electric field locally to a small portion of a larger device, or may be configured to provide an electric field to multiple devices or multiple multiferroic regions. A magnetic field stimulus also may be applied to all or a portion of the multiferroic medium **110** by any conventional method. Examples include an electromagnet and a permanent-pole magnet.

In some embodiments, a stimulus including an electric and/or magnetic field may be static. Herein, a static stimulus refers to a stimulus, such as a stimulus provided by the controller **130**, having a magnitude that does not vary substantially over a temporal period of a signal being modulated thereby, e.g. the input signal **140**. In other embodiments, the stimulus is nonstatic, meaning the stimulus may change on a time scale similar to or shorter than a period of the signal being modulated thereby.

In some cases, the response of the permittivity or the permeability of the multiferroic medium **110** to an external stimulus may be isotropic, e.g., having a negligible dependence on orientation of the medium relative to the stimulus. In other cases, the response may be anisotropic, e.g., the orientation of the medium in relation to the stimulus has a non-negligible effect on ∈ or μ. Additional anisotropy may also be induced by the shape of the material sample in some cases. Such shape anisotropy is typically most pronounced for soft magnetic materials.

A multiferroic medium may be a homogeneous or a heterogeneous crystalline material. A homogeneous material may be, e.g., a crystalline material with long-range periodicity of a primitive cell in which atoms are arranged in a manner that confers coupled ferroic properties. Such a medium is illustrated in FIG. **2**A, where a multiferroic material **210** has general lattice parameters a, b, and c. As a nonlimiting example, homogeneous multiferroic materials are expected to include some compounds with a perovskite structure.

In some cases, a homogenous multiferroic medium may include some cations selected to confer ferroelectric characteristics to the material, and others that confer ferromagnetic characteristics. For example, cations associated with ferroelectric characteristics include some group 3, 4 and 5transition metals, e.g., Cr. Cations associated with ferromagnetic characteristics include those of some elements with partially occupied d- and f-shells, e.g., Fe, Ni, Co, Gd and Dy. Cations of the material may be balanced by anions such as, e.g., O^{2-}, S^{2-}, and $(SO_4)^{2-}$. Thus, for example, it is expected that $CoFe_2O_4$ and chromium oxide may function as multiferroic materials over some temperature ranges.

In some cases, elements outside the group 3, 4 and 5 transition metals, such as Bi, e.g., may contribute ferroelectric properties. Nonlimiting examples of such materials include $BiFeO_3$ and $HoMnO_3$. A ferromagnetic or antiferromagnetic ordering temperature of such a composition may be below room temperature.

In some cases, the multiferroic material may be chemically relatively simple. Copper and Mn are two of a small number of elements, some cations of which may break inversion symmetry in a primitive cell of the lattice of the compound formed with a counterbalancing anion. One example is CuO, which typically requires cooling below 0° C. to allow the unit cells of the crystal lattice to assume a configuration that results in multiferroic properties.

FIGS. **2**B and **2**C illustrate examples of heterogeneous multiferroic media **220** and **230**, respectively. A heterogeneous multiferroic medium may provide a degree of freedom not provided by a homogeneous multiferroic material for producing the desired coupling between ferroelectric and ferromagnetic domains. Separate domains of, e.g., ferromagnetic and ferroelectric materials may be formed, with neighboring domains sharing an interface. The ferromagnetic and ferroelectric domains may comprise materials that do not easily form homogeneous compounds. When the domains share an interface the ferroelectric ordering of a ferroelectric domain may couple to the ferromagnetic ordering of a neighboring ferromagnetic domain, leading to multiferroic behavior.

FIG. **2**B illustrates an embodiment in which the multiferroic medium **220** includes alternating layers **240**, **250**. The layers **240**, **250** may respectively be, e.g., a ferroelectric material and a ferromagnetic material. In this case, coupling is generally over a two-dimensional interface. Generally, the response of the medium **220** to an external stimulus is expected to be anisotropic because of the planar nature of the medium **220**. While such anisotropy may limit the applications of the medium **220**, the layered structure may be formed in a manner that results in well-controlled material properties.

In some cases, the medium **220** may be used as a waveguide. Light may be configured to travel in the medium **220** with a propagation direction, e.g., Poynting vector, about parallel to the interface between the layers **240**, **250** to substantially maximize the interaction of the light with the interfaces. Such an orientation is expected to maximize the effect of modulating the permittivity and/or permeability of the medium **220**.

In some embodiments, the thickness of the layers **240**, **250** is no greater than about twice a depth over which the ferroelectric and ferromagnetic responses couple. This thickness may be, e.g., on the order of about 100 nm. In a nonlimiting example, 50 nm layers of $BaTiO_3$ (e.g., ferroelectric) alternating with 150 nm layers of $CoFe_2O_4$ or $BaFe_{12}O_{19}$ (e.g., ferromagnetic) is expected to exhibit multiferroic properties. Such a layered medium may be formed by various conventional material growth techniques, including, e.g., chemical vapor deposition (CVD), physical vapor deposition (PVD) and molecular beam epitaxy (MBE).

FIG. **2**C illustrates an embodiment in which the multiferroic medium **230** includes ferroelectric domains **260** and ferromagnetic domains **270**. The domains **260**, **270** are large

enough to exhibit crystalline properties, e.g., having a mean diameter greater than about 50 nm. The lattice orientations of the domains **260**, **270** have a pseudo-random distribution. Each domain **260**, **270** shares an interface with a neighboring domain **260**, **270**. When the neighboring domains are dissimilar materials, e.g., ferroelectric and ferromagnetic, the ferroelectric and ferromagnetic properties are expected to couple, leading to multiferroic behavior. Because the domains **260**, **270** are arranged pseudo-randomly, the multiferroic properties of the medium are expected to be substantially isotropic. The medium **230** may be advantageous in applications in which isotropic properties are desired, such as, e.g., capacitive or inductive elements or circuit substrates.

The medium **230** may be formed, e.g., by sintering intermixed particles of a ferroelectric material and a ferromagnetic material. Such a process will in general depend on the properties of the materials being sintered. As an illustrative example, a powdered quantity of $BaTiO_3$ may be uniformly dispersed with a powdered quantity of $CoFe_2O_4$ and/or $BaFe_{12}O_{19}$ with a ratio that results in approximately equal atomic percentages of Ti and Fe. The mean particle size in each sample may be about 100 nm or less. The mixed sample may be sintered at a temperature of 1200 C. for air for several days. Those skilled in the ceramic arts, e.g., are capable of determining appropriate processing conditions for other sintered hetero-multiferroic media.

Embodiments include a multiferroic material used as a dielectric or magnetically permeable medium in a passive component of an electrical circuit. The component may be configured to change a reactance in response to an external stimulus. For instance, FIG. **3**A illustrates an example embodiment of a capacitive element **300**. The capacitive element **300** is shown, e.g., as a parallel plate capacitor with plates **310** and a dielectric **320** therebetween. The configuration of the capacitive element **300** is illustrative of various configurations, including, e.g., comb and plate capacitors. In the capacitive element **300**, the dielectric **320** is a multiferroic medium. The capacitive element **300** is illustrated in a magnetic field H. Because the permittivity of the dielectric **320** is a function of H, varying the magnitude of H applied to the capacitive element **300** may modulate the capacitance thereof. Varying H will also generally modulate the RI.

In another embodiment, a multiferroic medium such as the dielectric **320** may be a gate dielectric of a FET or a MOSFET. Such a FET or MOSFET may be used, e.g., as a magnetic field sensor, because the gate dielectric has a dielectric permittivity that is responsive to changes in an external magnetic field.

FIG. **3**B illustrates an embodiment of an inductive element **330**, illustrated as a planar coil **340**, e.g. The planar coil **340** is formed on a substrate **350** that includes a multiferroic material. The inductive element **330** is shown with an applied electric field E. Because the permeability of the substrate **350** is a function of E, the inductance of the coil **340** may be altered by changing the magnitude of E applied to the substrate **350** under the coil **340**.

Embodiments include passive/reactive electrical circuits with components that include multiferroic dielectrics and magnetically permeable media. The response of the multiferroic medium to an external stimulus provides a means to tune an operating characteristic of an electronic device whose operation is affected by the permittivity or permeability of the multiferroic medium. Further embodiments include active components in combination with passive components.

In an embodiment illustrated in FIG. **4**, a reactive network **400**, e.g., an L-C (inductive-capacitive) network, may have an impedance $Z(\omega)$ that depends on the impedance of one or more capacitors **410** or inductors **420** in the network. The reactive network **400** is shown without limitation as, e.g., a two-port network. The impedance may be, e.g., an input impedance at ports **1** and **2**. In the reactive network **400**, one or more of the capacitors **410** and/or inductors **420** include a multiferroic medium. Thus, the capacitance and/or inductance of one or more these elements of the reactive network **400** may be changed by applying an external stimulus, e.g., an external electric or a magnetic field, or a mechanical stress or strain, to the one or more elements. Such stimuli can thereby change the impedance of a portion of the reactive network **400** and/or electrical resonance characteristics of the portion of the reactive network **400**.

In some embodiments, the reactive network **400** may include an antenna that has an impedance that depends on a dielectric permittivity or magnetic permeability of a multiferroic material. For example, the antenna may have a radiating element that has a distributed capacitance or inductance that is determined in part by a multiferroic medium electromagnetically coupled to the radiating element. For example, the multiferroic medium may be used as a substrate upon which radiating elements may be formed. An externally applied stimulus, e.g., electric or magnetic field or mechanical stress, may be applied to change the distributed capacitance or inductance, and thereby the impedance of the antenna. Thus, the radiative properties and/or gain of the antenna may be modulated by the external stimulus.

In another embodiment the reactive network **400** may terminate a signal path, such as a waveguide or high speed signal path, that has a characteristic impedance that varies with time. The input impedance of the network may be controlled by, e.g., an external controller that changes the dielectric permittivity or magnetic permeability of one or more components of the network to maintain an impedance match between the signal path and the reactive network **400**.

Various embodiments of electronic circuits include capacitive and/or inductive elements having multiferroic materials therein. For example, a radio-frequency transmitter or receiver may include an electrical filter with passband characteristics determined in part by the capacitance or inductance, respectively, of a capacitor or inductor having a multiferroic material therein. In such embodiments, the capacitive element **300** and the inductive element **330** may enable the tuning of a frequency of operation of the transmitter or receiver by the application of an electric or magnetic field to the circuit element(s) that includes a multiferroic material.

FIGS. **6**A and **6**B illustrate a plan and sectional view, respectively, of an embodiment of a device **600** in which an electromagnetic signal **610** propagates via a waveguide **620**. The waveguide **620** includes a core **630** and a cladding **640**.

In a first embodiment, the core **630** is a conventional optical medium that is transparent to an optical signal wavelength of interest, such as silicon or SiO_2. Herein and in the claims, an optical signal has a frequency in the IR, visible or UV range, generally taken to be in a range of about 30 THz to about 1 PHz. The cladding **640** is a multiferroic material that has an index of refraction that can be changed by the application of a magnetic or electric field, or by a mechanical stress. The field may be applied, e.g., by electrodes **645***a*, **645***b* formed on upper and lower surfaces of the cladding **640**. Upper electrode **645***a* and lower electrode **645***b* may be oppositely charged to modulate the RI of the cladding.

In an example, the core **630** may be a planar optical waveguide formed over a substrate **635**. The core may have a width of about 0.75 μm and a thickness of about 5 μm. These dimensions are suitable to transmit an optical electromagnetic signal **610** having a wavelength of about 1.3 μm, e.g.

The cladding **640** may be formed, adjacent the core **630**, e.g., by conventional methods, and may optionally also cover the core **630**.

The optical signal **610** is substantially confined to propagate in the waveguide **620** when the RI of the optical cladding **640** is less than that of the core **630**. An external stimulus, e.g., the potential applied across the electrode **645***a*, **645***b*, may be used to modulate the permeability of the cladding **640**, thus changing the index of refraction of the cladding **640** and thereby changing a transmission characteristic of the waveguide **620**. For example, the RI of the cladding **640** may initially be less than that of the core **630**, resulting in total internal reflection of a propagating light signal in the core **630**. Application of the external stimulus **650** may cause the RI of the cladding **640** to become greater than that of the core **630**, resulting in leakage of light from the core **630**. Thus, an output signal **670** may be controllably attenuated relative to the input optical signal **610**. In some embodiments, the RI is changed by the application of a magnetic field, or by stress or strain on the cladding **640**.

In a second embodiment of the device **600**, the core **630** is formed from a multiferroic material, and the cladding **640** is formed from a conventional cladding material. The RI of the core **630** varies in response to the stimulus **650** from a value less than the RI of the cladding **640** to a value greater than the cladding **640**. Thus, in a manner analogous to the illustrated embodiment of the waveguide **620**, the output signal **670** may be controllably attenuated.

In other embodiments, a waveguide may be configured to propagate microwave or terahertz frequencies. A microwave band may include frequencies in a range of about 300 MHz to about 3 GHz. A terahertz band may include frequencies in a range of about 30 THz to about 400 THz. In such cases, the cladding **640** may be metallic, and the core **630** may include a multiferroic medium. In such cases, the stimulus **650** may be limited to a magnetic field or a stress/strain. The stimulus **650** may change the $\in$ and/or μ of the core **630**, altering the propagation characteristics of the microwave or terahertz signal therein. For example, the change $\in$ and/or μ may change the impedance of the waveguide **620**.

In some embodiments, the multiferroic material is configured to tune a frequency range over which a medium acts as a metamaterial. A metamaterial is a medium having a negative RI, or that exhibits negative refraction. The RI has a negative sign when both the dielectric constant and magnetic permeability have negative real parts at a particular frequency. The negative RI causes electromagnetic radiation of the particular frequency to refract abnormally at interfaces between the metamaterial and media with positive refractive indexes. In abnormal refraction, incident and refracted light rays lie on the same side of the normal to the interface in the incidence plane.

To illustrate, FIG. **7** illustrates an example of a permittivity characteristic and a permeability characteristic of an example metamaterial as a function of frequency. Both $\in$ and μ are negative in a frequency range **710**. Because both $\in$ and μ are negative, the RI of the example medium is negative, and the medium is a metamaterial in this frequency range.

In some cases, a multiferroic medium is a material that may exhibit metamaterial behavior over a frequency range. See, e.g., A. Pimenov, et al., Negative Refractive Observed in a Metallic Ferromagnet in the Gigahertz Frequency Range, PRL 98, 197401 (1997). The frequency range may be changed by altering the frequency at which $\in$ and/or μ become negative. In other cases, a metamaterial is a composite periodic structure that includes a multiferroic material. A multiferroic material may be used to tune the frequency range **710** over which $\in$ and μ of the metamaterial are negative. This tuning may be done by changing the permittivity and/or permeability of portions of the multiferroic material placed at suitable locations in the metamaterial.

FIG. **8**A illustrates an example metamaterial **800**. A similar metamaterial is described in U.S. Pat. No. 7,015,865 to Isaacs, et al., incorporated herein by reference in its entirety. The metamaterial **800** is formed of a number of unit cells. A unit cell is shown in FIG. **8**B, and includes two dielectric substrates **810**, and a number of split ring resonators (SRRs) **820**, three each of SRRs **820***a* and **820***b*.

FIG. **8**C illustrates a single SRR **820**. The SRR **820** includes a reactive component comprising two split rings **830** on a multiferroic slab **840**. The example split rings **830** are fabricated of a 0.03 mm thick copper layer and may have various ring-like shapes. The example SRR **820** has feature dimensions that satisfy: c=0.25 mm, d=0.30 mm, g=0.46 mm, and w=2.62 mm. The concentric metallic split rings **830** form a circuit element whose capacitance depends on the dielectric permittivity of the underlying multiferroic slab **840**.

In an embodiment, the multiferroic slab **840** is formed of a multiferroic medium whose permittivity is a function of an applied external electric field normal to the surface of the slab. When the electric field is applied, the capacitance of the split rings **830** also changes. Referring to FIG. **8**B, when an electric field is applied along the x axis, the capacitance of the SRRs **820***b* changes. When an electric field is applied along the y axis, the capacitance of the SRRs **820***a* changes. When either or both sets of SRRs **820***a*, **820***b* are caused to change capacitance due to the applied field(s), the frequency over which the metamaterial **800** has $\in$ and μ simultaneously negative changes. The frequency over which the metamaterial **800** has a negative RI thereby also changes. Thus, the external stimulus, e.g., the applied electric field, may change an operational characteristic of a device utilizing the multiferroic metamaterial **800**.

The metamaterial **800** may be located in a propagation path of an electromagnetic signal. In some cases, the signal may propagate without spatial confinement (free-space propagation). In other cases, the signal me be confined by, e.g., a waveguide.

FIGS. **9-13** illustrate various embodiments of apparatus that may use a multiferroic medium that in some embodiments is also a metamaterial at some frequencies. Turning first to FIG. **9**, illustrated is an example embodiment of an optical wavelength converter **900**. A similar device is described in U.S. patent application Ser. No. 11/432,803, "Nonlinear Optical Devices Based on Metamaterials" by Chowdhury, et al., incorporated herein by reference in its entirety. Briefly described, the wavelength converter **900** includes a pump source **910**, optical waveguides **920**, **925**, an optical connector **930**, and a filter **940**, all of which may be fabricated using methods well known to those of skill in the art. In an embodiment, dimensions of the various components of the wavelength converter **900** are selected such that the wavelength converter **900** is operable to convert a wavelength of about 1550 nm to about 775 nm. An optical conversion medium **950** is a metamaterial for light at a frequency of one or more of input light to be wavelength-converted, the pump light, and the wavelength-converted light. At least a portion of the optical conversion medium **950** is a multiferroic medium that is at least partially transparent to the frequency of light passing through the medium **950**.

The wavelength of operation of the wavelength converter **900** depends in part on the frequency range over which the optical conversion medium **950** behaves as a metamaterial, e.g., has a negative RI. An external stimulus **960**, e.g., an

electric and/or magnetic field, or a mechanical stress and/or strain, is applied to the optical conversion medium **950**. In one embodiment, the external stimulus **960** may be varied to alter the frequency range over which the optical conversion medium **950** behaves as a metamaterial. In another embodiment, the magnitude of the RI at a particular frequency may be changed by varying the external stimulus **960**. Thus, the external stimulus **960** may used, e.g., to make fine adjustments to the RI of the optical conversion medium **950** to alter an operational characteristic of the wavelength converter **900**. An operational characteristic may be, e.g., wavelength conversion via a negative RI medium as opposed to wavelength conversion with a positive RI medium.

In some embodiments, the optical conversion medium **950** is a multiferroic with a nonlinear optical response. Such a material may have, e.g., a Perovskite structure. In a nonlimiting example, bismuth manganite ($BiMnO_3$) is used as the medium **950**. A 5 μm $BiMnO_3$ layer may be formed, e.g., as an epitaxial layer on a suitable substrate such as, e.g., $SrTiO_3$. The $BiMnO_3$ may be patterned and etched using conventional methods such as, e.g., a nonselective sputter etch to form an optical path. The width of the path may be, e.g., about 2 μm. The optical waveguides **920**, **925** and the optical connector **930** may be formed from, e.g., a PMMA layer lithographically patterned by conventional methods. The PMMA layer may be cast in place after forming the medium **950** to provide a low insertion-loss interface between the optical connector **930** and the optical waveguide **925**.

FIG. **10** illustrates an embodiment of a polarization diverse (PD) apparatus **1000** in which an optical path may include a metamaterial. The general operation of a similar PD apparatus is described in U.S. patent application Ser. No. 11/586,290, "Polarization-Diverse Negative-Refractive-Index Apparatus and Methods" by Chowdhury, incorporated herein by reference in its entirety. Briefly described, the PD apparatus **1000** includes a splitter **1010**, optical path **1020**, polarization rotators **1030** and a polarization sensitive negative RI (PS NRI) medium **1040**. The medium **1040** may be, e.g., $BiMnO_3$ processed as previously described. The relevant dimensions of the structural elements of the apparatus **1000** may be determined by one skilled in the optical arts in light of specific application requirements.

The NRI medium **1040** produces an optical effect on an optical signal passing therethrough, meaning the NRI medium **1040** may alter, modulate or otherwise change one or more parameters, e.g., amplitude or phase, of the EM signal.

Because the (negative) RI of the medium **1040** is a function of the permittivity and the permeability thereof, the effect produced by the medium **1040** may be modulated by subjecting the medium **1040** to an external stimulus **1050** (electric or magnetic field, or stress/strain). The stimulus **1050** may be applied, e.g., by electrodes or an external coil. Thus, the apparatus **1000** may be tuned, e.g., by the external stimulus to precisely control the effect produced on the EM signal.

FIG. **11** illustrates an embodiment of an NRI device **1100** for generating terahertz or microwave radiation. The operation of a similar device is generally described in U.S. patent application Ser. No. 11/942,776, "Negative Refractive Index Device for Generating Terahertz or Microwave Radiation and Method of Operation Thereof" by Chowdhury, et al. (the '776 Application), incorporated herein by reference in its entirety. The NRI device **1100** includes a pump source **1110**, an optical path **1120**, an optical coupler **1130**, and an NRI medium **1140**, and produces EM radiation **1150**. The NRI medium **1140** behaves as a metamaterial at a center frequency of light pulses produced by the pump source **1110**. The medium **1140** also exhibits a second-order nonlinearity proximate the center frequency of the pulse and the output radiation of interest. The frequency of the EM radiation **1150** output by the NRI device **1100** is dependent in part on the center frequency. The medium **1140** may comprise, e.g., $BiMnO_3$.

As described in the '776 Application, the light pulses enter and propagate through the NRI medium **1140**. The pulses have an associated group velocity ($d\omega/dk$) that depends upon the RI. A resonance occurs in the medium **1140** producing light with a phase velocity ω/k that may be a function of the group velocity.

The NRI medium **1140** is a multiferroic material and a metamaterial. Thus, an external stimulus **1160**, e.g., an electric and/or magnetic field as described with respect to, e.g., the apparatus **1000**, may change the $\in$ and/or the μ of the medium **1140**. The change of $\in$ and/or the μ may thereby change the group velocity of the light pulses and/or the resonant frequency of the medium **1140**. For example, the RI may change from one negative value to another negative value. The change of resonant frequency changes the dispersion characteristics of the medium **1140**. The medium **1140** may be used in combination with a tunable pump source **1110**. For example, the center frequency of the light pulses output by the pump source **1110** can be tuned to match the change of the dispersion characteristic of the medium **1140**, thereby changing the frequency of the radiation output by the NRI device **1100**.

FIG. **12** illustrates an embodiment of a device **1100** configured to respond resonantly to an applied electric field. The general operation of a similar device is described in U.S. Pat. No. 6,661,392 to Isaacs, et al., incorporated herein by reference in its entirety. A dielectric or magnetically permeable object **1210** includes a multiferroic medium for which at least $\in$ or μ is negative at a frequency of a signal propagating as E_{far}. At a resonant frequency determined in part by the geometry of the object **1210**, an electrical signal may be is produced at terminals **1220**, **1230**. The response of the device **1200** is resonant over a selected wavelength range so that the device **1200** may be an antenna for a radio frequency signal even though the signal has a wavelength that is much larger than a dimension D of the object **1210**.

In some embodiments, the frequency at which the object **1210** is resonant is determined in part by the value of $\in$. The value of $\in$ may be tuned by application of an external stimulus **1240**, e.g., a magnetic field. Thus, by changing the magnetic field, the resonant frequency of the object **1210** may be controllably changed, thereby tuning the frequency to which the device **1200** is sensitive.

Finally, FIG. **13** illustrates a structure **1300** of a phased array antenna system. A similar antenna system is described in detail in U.S. Pat. No. 6,958,729 to Metz, et al., incorporated herein by reference in its entirety. The structure **1300** includes, e.g., three unit cells on a substrate **1310**. Each unit cell includes an inductor **1320** and a capacitor **1330**. The inductor **1320** and the capacitor **1330** may operate, e.g., to delay a phase of a signal on a microstrip line **1340**. Phase delays on multiple microstrip lines may be configured to produce a desired gain pattern of a phased array antenna, e.g. The substrate **1310** includes a multiferroic medium. An external stimulus **1350**, e.g. an electric and/or a magnetic field, may change the permittivity or the permeability of the substrate **1310**, thereby changing the capacitance of the capacitor **1330** or the inductance of the inductor **1320**. Thus, the phase delay on the microstrip line **1340** may be tuned by the application of the stimulus **1350**, providing a means to vary the gain pattern of the antenna.

Turning to FIG. **5**, a method **500** of the disclosure is presented. The method begins with a step **510**. In a step **520**, a

waveguide that includes a multiferroic medium is configured to propagate an electromagnetic signal. In a step **530**, a mechanical strain, or a control electrical or magnetic field is applied to the waveguide such that the applying changes a permittivity or a permeability of the medium. In a step **540**, the electromagnetic signal is propagated through the waveguide while performing the applying. The method **500** ends with a step **550**.

FIG. **14** presents a method **1400** of the disclosure. The method begins with a step **1410**. In a step **1420**, a metamaterial including a multiferroic medium is located in a propagation path of an electromagnetic signal. In a step **1430**, an electric or magnetic field is applied to the metamaterial. The application of the field changes a permittivity or permeability of the medium. In a step **1440**, a propagation characteristic of the electromagnetic field is altered by the application of the field. The method **1400** ends with a step **1450**.

Although the present invention has been described in detail, those skilled in the art should understand that they can make various changes, substitutions and alterations herein without departing from the spirit and scope of the invention in its broadest form.

What is claimed is:

1. An apparatus, comprising:

a waveguide including a multiferroic medium including at least one ferroelectric domain and at least one ferromagnetic domain that shares an interface with said ferroelectric domain; and

a controller configured to apply a mechanical strain or a control electric or magnetic field to said multiferroic medium,

wherein said multiferroic medium has a dielectric permittivity or magnetic permeability that is responsive to said strain or said control field.

2. The apparatus as recited in claim **1**, wherein said waveguide is configured to propagate optical frequencies.

3. The apparatus as recited in claim **1**, wherein said waveguide is configured to propagate terahertz frequencies.

4. The apparatus as recited in claim **1**, wherein a transmission characteristic of said waveguide is changed in response to said strain or said control field.

5. The apparatus as recited in claim **1**, wherein said medium is a metamaterial over a first frequency range.

6. The apparatus as recited in claim **5**, wherein said medium behaves as a metamaterial over a different second frequency range in response to said strain or said control field.

7. An apparatus, comprising:

a plurality of unit cells, each unit cell including:

a multiferroic substrate; and

a reactive component supported by said substrate,

wherein said plurality of unit cells is configured to act as a metamaterial over a frequency range.

8. The apparatus of claim **7**, wherein said plurality is configured such that said frequency range changes in response to an applied electric or magnetic field.

9. The apparatus as recited in claim **7**, wherein said multiferroic substrate comprises a heterogeneous multiferroic material.

10. The apparatus as recited in claim **1**, wherein:

said at least one ferroelectric domain includes a first continuous material layer;

said at least one ferromagnetic domain includes a second continuous material layer; and

said first and second material layers share an interface.

11. The apparatus as recited in claim **10**, wherein said interface is about planar.

12. The apparatus as recited in claim **1**, wherein said at least one ferroelectric domain includes one of a plurality of ferroelectric layers and said at least one ferromagnetic domain includes one of a plurality of ferromagnetic layers, said ferroelectric layers alternate with said ferromagnetic layers, and each ferroelectric layer shares an interface with at least one of said ferromagnetic layers.

13. The apparatus as recited in claim **1**, wherein:

said multiferroic medium includes a plurality of non-contiguous ferroelectric domains and a plurality of non-contiguous ferroelectric domains; and

said ferroelectric domains each share an interface with at least one of said ferromagnetic domains.

14. The apparatus as recited in claim **13**, wherein each of said domains includes a crystalline lattice, and the crystalline lattices of said pluralities are oriented pseudo-randomly.

15. The apparatus as recited in claim **7**, wherein said multiferroic substrate comprises a multiferroic medium including at least one ferroelectric domain and at least one ferromagnetic domain that shares an interface with said ferroelectric domain.

16. The apparatus as recited in claim **15**, wherein:

said at least one ferroelectric domain includes a first continuous material layer;

said at least one ferromagnetic domain includes a second continuous material layer; and

said first and second material layers share an interface.

17. The apparatus as recited in claim **16**, wherein said interface is about planar.

18. The apparatus as recited in claim **15**, wherein said at least one ferroelectric domain includes one of a plurality of ferroelectric layers and said at least one ferromagnetic domain includes one of a plurality of ferromagnetic layers, said ferroelectric layers alternate with said ferromagnetic layers, and each ferroelectric layer shares an interface with at least one of said ferromagnetic layers.

19. The apparatus as recited in claim **15**, wherein:

said multiferroic medium includes a plurality of non-contiguous ferroelectric domains and a plurality of non-contiguous ferroelectric domains; and

said ferroelectric domains each share an interface with at least one of said ferromagnetic domains.

20. The apparatus as recited in claim **19**, wherein each of said domains includes a crystalline lattice, and the crystalline lattices of said plurality are oriented pseudo-randomly.

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